Thermal Testing of a Mars 2020 Enhanced Engineering Camera

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Mars 2020 Enhanced Engineering Cameras (EECAMs)

- The technology of the old MER/MSL ECAMs is well over a decade old and obsolete, so the Mars 2020 mission is introducing a new, more powerful camera called the *enhanced* engineering camera (EECAM)

9 total EECAMs

6x enhanced HazCams:

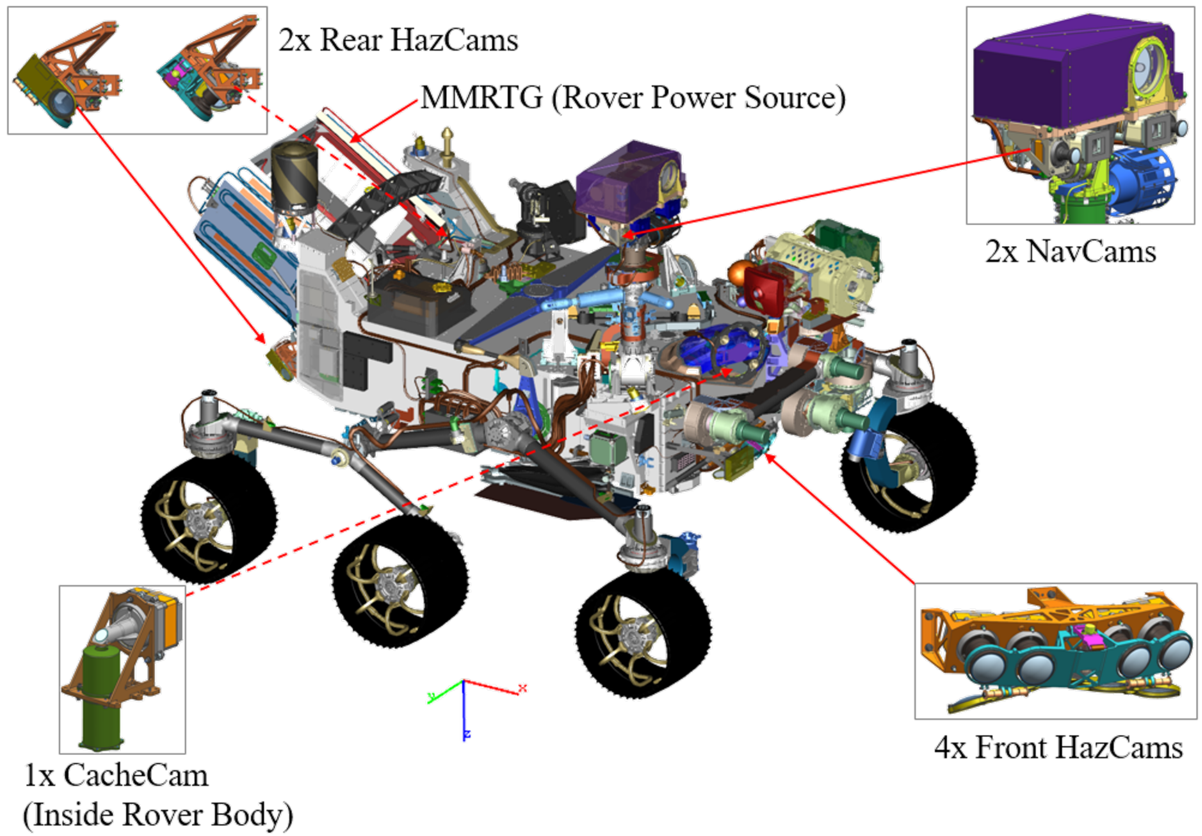
- 2x at the rear of the rover, on either side of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)
- 4x at the front of the rover, beneath the Robotic Arm

2x enhanced NavCams:

- At the base of the Remote Sensing Mast (RSM) head

1x newly designed CacheCam (Caching Camera)

- Inside the Adaptive Caching Assembly (ACA) as part of the rover's new Sampling and Caching Subsystem (SCS)



Thermal Design Overview

Thermal-Optical Coatings

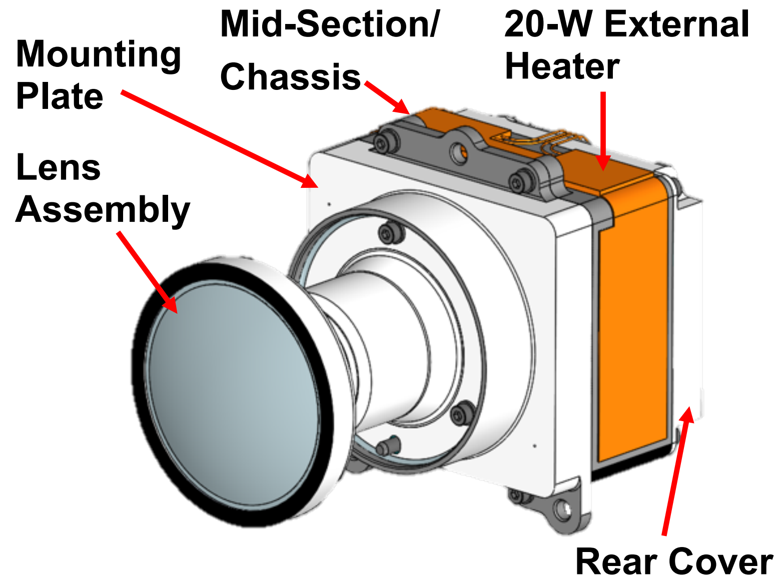
- Most surfaces of the HazCams/NavCams are painted white to reflect sunlight in hot cases
- Some smaller areas are black anodized
- CacheCam camera body is bare aluminum while its lens is black anodized

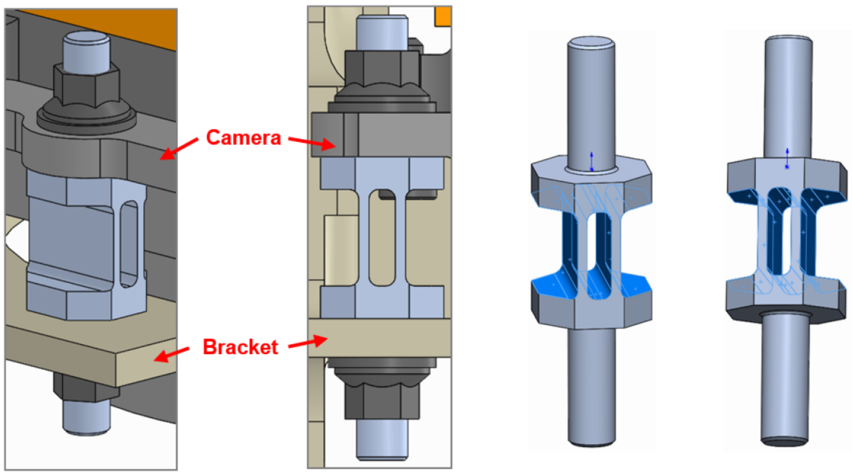
Heater

- 20-W Kapton film heater located on the camera body to warm up camera electronics and lens assembly to their operating temperature limits
- Controlled with flight software using PRTs located on the camera housing

Mounting Interface

- Each camera mounted to its bracket via three titanium thermal isolators





Testing Overview

- Validation of the EECAM thermal design during protoflight testing or rover system thermal testing would have been limited by the extent to which thermocouples could be instrumented on a flight camera unit
    - Warmup heaters are used to warm the electronics and lens assemblies to their minimum operational temperature limits – these components could not be instrumented due to the risk of damage
- For a more complete validation of the thermal design, testing was done on an engineering development unit (EDU) rather than on a flight model (FM)
- A follow-up test was done several months after the EDU test to characterize the thermal isolators used during the EDU test as well as the flight thermal isolators

EDU Test Objectives

- The primary objective of the EDU test was to gather transient and steady-state warmup data for the EECAM EDU for the purposes of thermal model correlation and subsequent thermal design validation
    - This was done in two environments: vacuum and 6 torr GN_2
    - Warmup was done using the camera housing GSE heaters

- A secondary test objective was to demonstrate the functionality of the EECAM electronics over the qualification temperature range (-70°C to 70°C) (not covered here)

EDU Test Article Overview

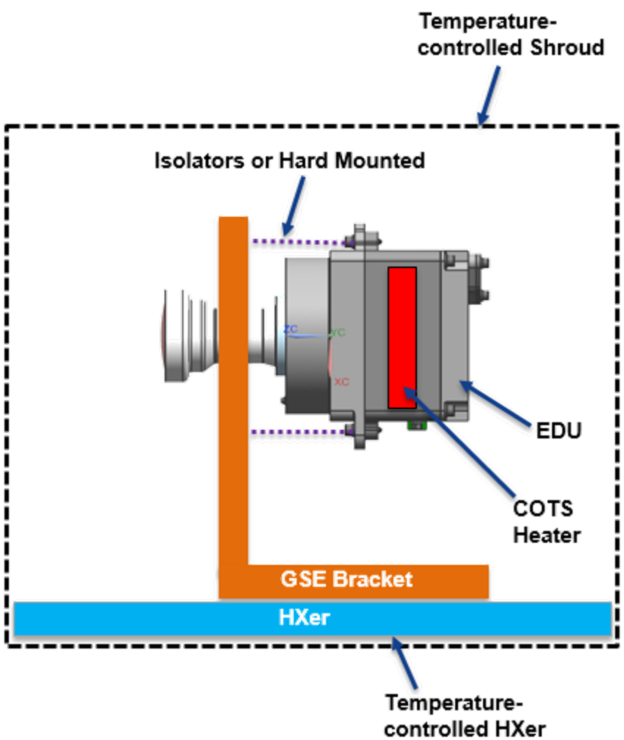
- The EECAM EDU test was flight-like, with a few exceptions listed below:

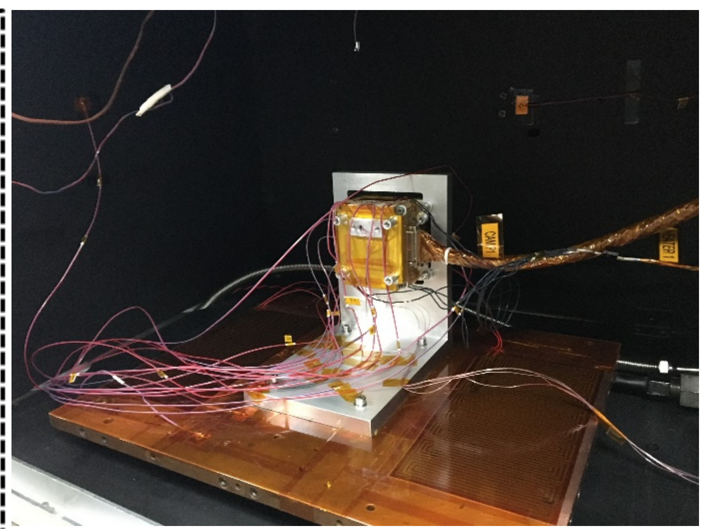
Design Feature	Flight Models	EDU
Detector Flexure Frame Material & Coating	Al 7075-T7351 Black Anodized	Al 6061-T6 Bare Aluminum
Camera Housing Surface Coatings	Interior: Black Anodized Exterior: White Paint for Haz/NavCam Bare Aluminum for CacheCam	Interior: Bare Aluminum Exterior: Kapton Tape
Camera Heater	3x COTS Heaters (157 Ω each)	1x Custom Heater (34 Ω)
Heater Control	PRTs and Rover Flight Computer	Single Thermocouple & External On/Off Temperature Controller
Mounting Interface to Bracket	3x Titanium Flight Isolators	Either 3x M4 Fasteners or 3x G10 EDU Isolators
Lens Barrel Surface Coatings	Interior: Black Anodized Exterior: White Paint for Nav/HazCam Black Anodized for CacheCam	Interior: Bare Aluminum Exterior: Z306 Black Paint

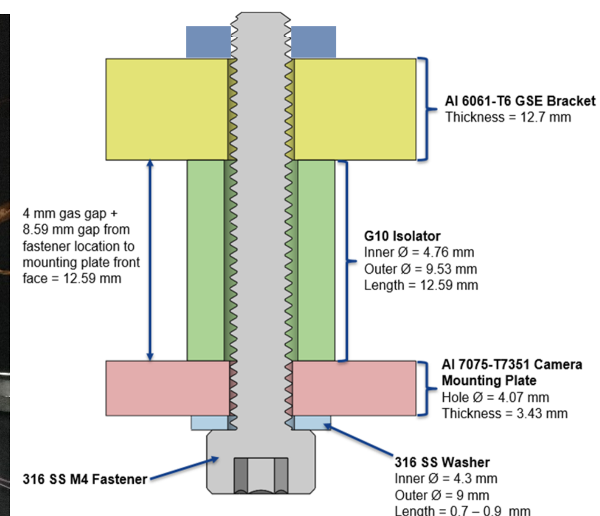
- A mass-thermal model (MTM) of the HazCam lens was used for this test – its dimensions, materials, interfaces, and conductive paths were identical to those of the flight units

EDU Test Setup

- The EDU was mounted to an aluminum GSE bracket (via either fasteners or G10 thermal isolators), which was then mounted to a copper heat exchanger
    - G10 isolators were designed to have a 0.013 W/K conductance and perform consistently in both vacuum and low pressure nitrogen testing
- The entire assembly was placed inside a temperature-controlled shroud

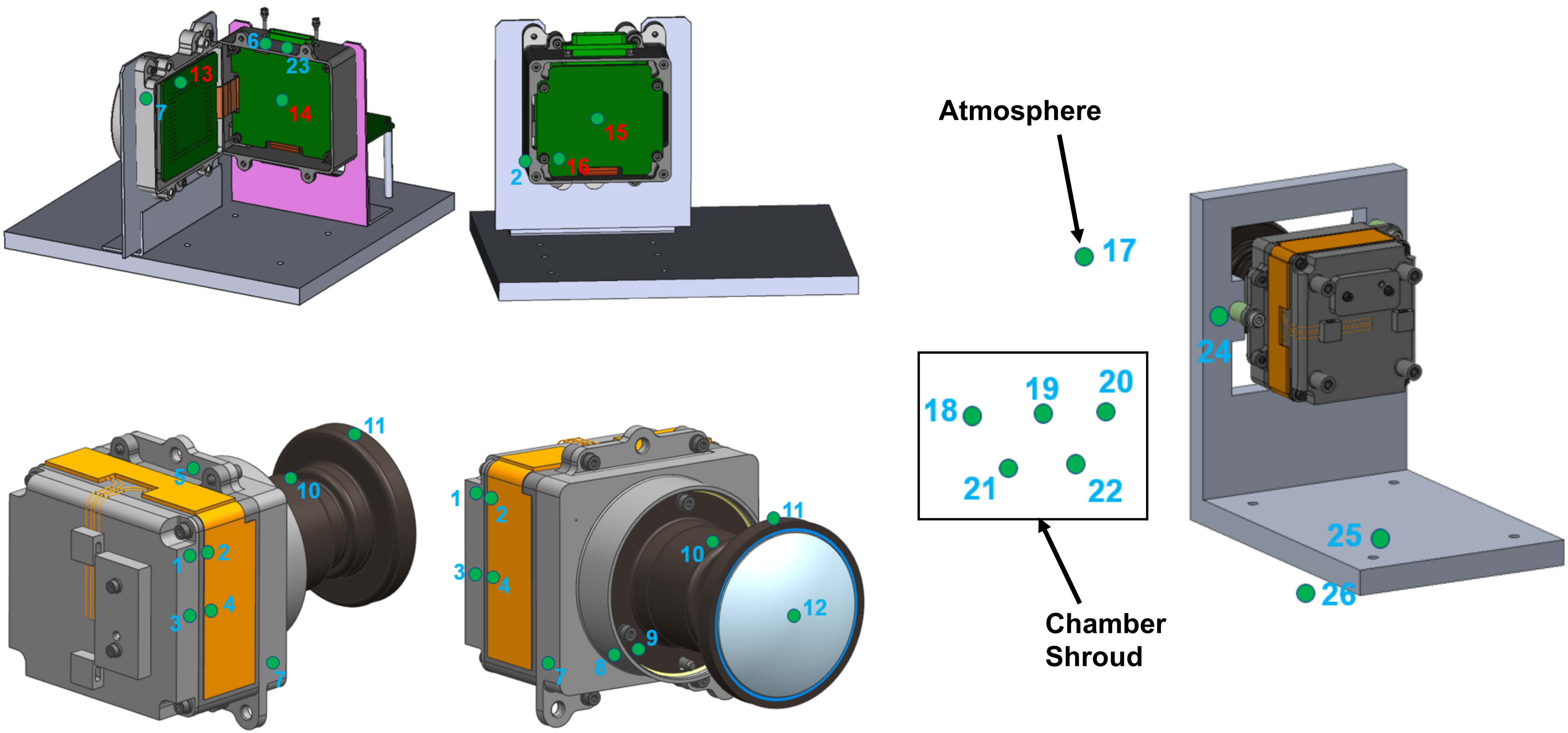






EDU Thermocouple Locations

- 27 total thermocouples used – 16 on the camera, and 11 on the chamber and GSE components



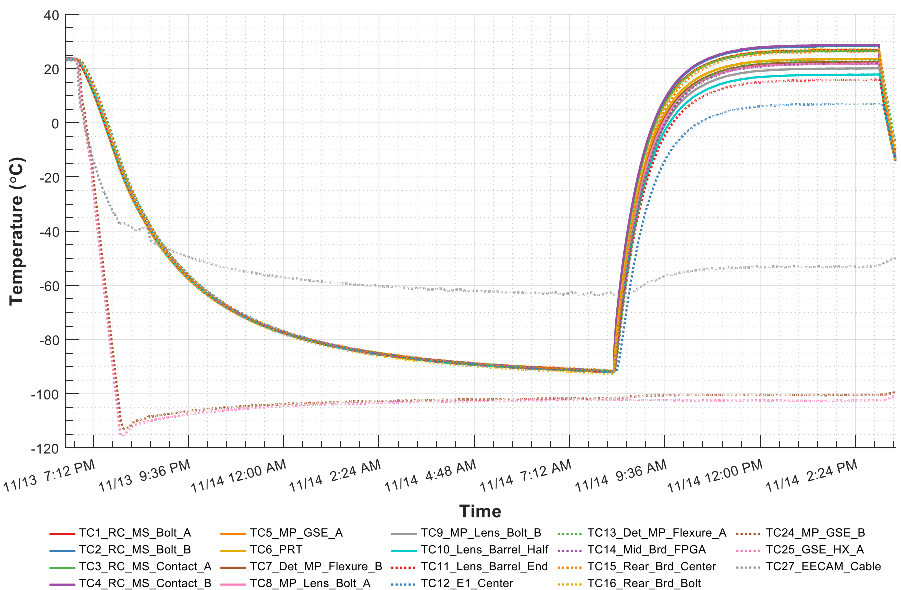
Test Matrix

Test Case	Description	Atmosphere	Pressure (Torr)	HXer Setpoint (°C)	Camera Htr Setpoints (°C)	Camera Htr Power (W)	Camera Operation	Start Date and Time	End Date and Time	Duration
1.1a	Hot Functional Test #1	GN_2	6 +/-1	82	N/A	0	On	11/07/17 2:00 PM	11/07/17 6:40 PM	4 hrs 40 min
1.1b	Hot Functional Test #2	GN_2	6 +/-1	82	N/A	0	On	11/08/17 12:20 PM	11/08/17 4:50 PM	4 hrs 30 min
1.2	Cold Functional Test	GN_2	6 +/-1	-70	N/A	0	On	11/09/17 8:50 AM	11/09/17 2:30 PM	5 hrs 40 min
CHAMBER BREAK										
2.1	Vacuum Cool Down	Vacuum	~6E-5	-100	N/A	0	Off	11/13/17 6:30 PM	11/14/17 8:20 AM	13 hrs 50 min
2.2	Vacuum Warmup	Vacuum	~6E-5	-100	57 and 63	12	Off	11/14/17 8:20 AM	11/14/17 3:00 PM	6 hrs 40 min
2.3	GN_2 Cool Down	GN_2	6 +/-1	-100	N/A	0	Off	11/15/17 9:15 AM	11/15/17 1:10 PM	3 hrs 55 min
2.4	GN_2 Warmup	GN_2	6 +/-1	-100	57 and 63	12	Off	11/15/17 1:10 PM	11/15/17 5:55 PM	4 hrs 45 min
2.5	Vacuum Cool Down	Vacuum	~6E-5	-110	N/A	0	Off	11/15/17 6:10 PM	11/16/17 10:16 AM	16 hrs 6 min
2.6	GN_2 Flight-like Warmup	GN_2	6 +/-1	-110	-50 and -44	20	Off/On	11/16/17 10:16 AM	11/16/17 1:40 PM	3 hrs 24 min

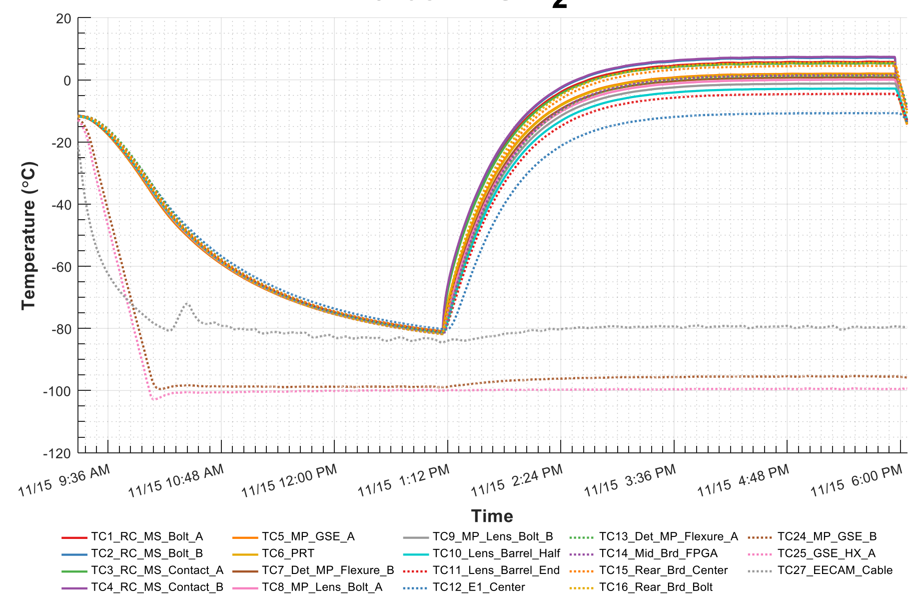
Steady State Warmup Test Cases

- Camera temperatures were about 20°C warmer than expected
- Overall camera gradients were about 15°C lower than originally predicted by model results

Vacuum:

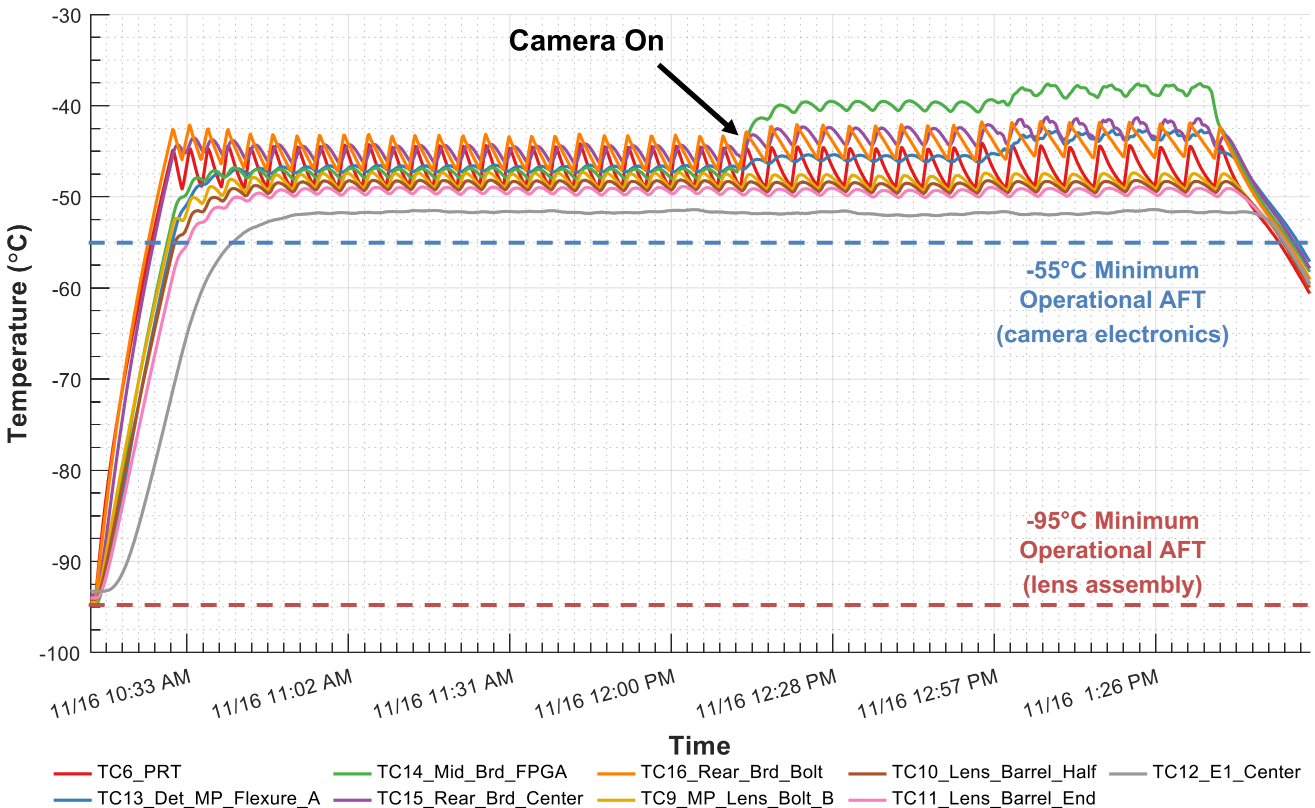


6 torr GN_2:



Flight-like Warmup and Maintenance Heating

- Overall warmup time from -95°C to -55°C was about 15 minutes
- Heater duty cycle with the camera off was 27%
    - With the camera on, the duty cycle dropped to 25%
    - With the camera on in its most thermally-stressful mode, the duty cycle was 22%



EDU Model Correlation Overview

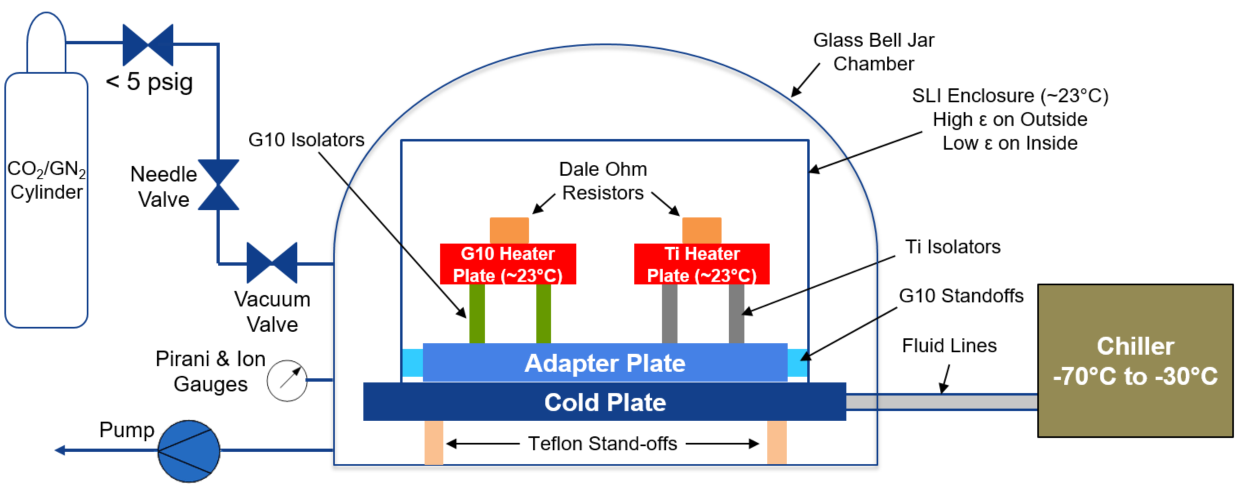
- For the vacuum and GN_2 steady state and transient warmup cases, the goal was to correlate temperatures to within 5°C of the test data
- For the GN_2 flight-like warmup the goal was to also correlate to within 5°C of the test data, as well as correlate the duty cycle to within 5% of test data
- In general, emphasis was placed on the electronics and lens assembly correlation
- In areas of uncertainty, properties were biased towards more conservative values

EDU Model Correlation Results

- Nearly all vacuum and GN_2 model temperatures were correlated to within 2°C of the test data – exception was the PRT temperature, which was purposely off by 3-4°C for conservatism
- Overall, most parameter changes involved increases in conductance values to drive the overall camera gradients down
- The most significant change was the reduction of the G10 thermal isolator conductance from what was previously assumed (0.013 W/K)
    - Correlated vacuum value: 0.004 W/K (3x less than expected)
    - Correlated GN_2 value: 0.009 W/K (2x less than expected)
- Initial assumption was that the fastener at the center of the isolator would have good contact against the camera and bracket, meaning the conductance could be evaluated using the conduction through the fastener and the conduction through the G10
- Most of the heat flow was through the G10, which is more noticeable in the vacuum case
    - With the presence of GN_2, gas conduction reduced the resistance between fastener and camera/bracket, increasing the overall conductance

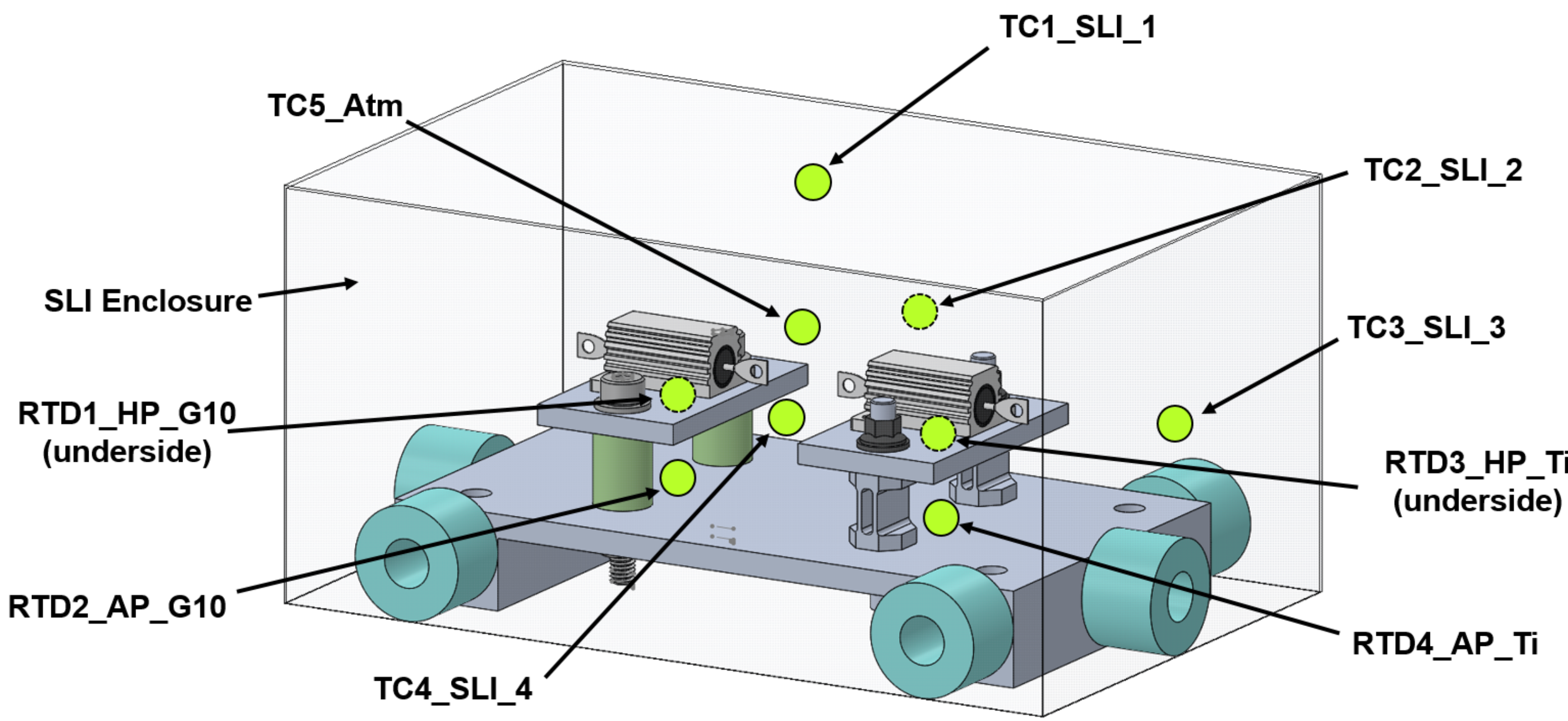
Thermal Isolator Test Overview

- As a follow-up to the EDU thermal test, an additional thermal test was done to verify the correlated values of the G10 isolators and to test the conductance of the flight titanium isolators
- 4 thermal isolators were tested: one pair of G10 isolators from the EDU test and one pair of the flight titanium isolators
- Two heater plates present, each with a heater and a pair of isolators (controlled to ~23°C)
- Assembly was mounted to an adapter plate and then bolted to a heat exchanger cold plate
- SLI enclosure made of double-aluminized Mylar enveloped the heater plates and adapter plate – it had three purposes
    - Limit radiative heat transfer between the heater plates and the room
    - Sized small enough to ensure no convection cells would form
    - Track as closely to room temperature as possible – exterior was covered in black Kapton tape



Thermal Isolator Test Instrumentation

- 9 temperature sensors used
  - 4 RTDs placed on the heater plates and adapter plate
  - 5 thermocouples placed on various faces of the SLI enclosure



Thermal Isolator Test Matrix

- Steady state testing was done at three cold plate temperatures and in three environments
  - -30°C, -50°C, & -70°C
  - Vacuum, 6 torr GN_2, & 10-20 torr CO_2 (pressure measurement issues resulted in CO_2 testing being done in 10-20 torr rather than in 6 torr as desired)
- Each heater plate power was adjusted to keep the heater plate at ambient temperature
  - Ambient temperature was chosen to minimize the parasitic heat transfer between the heater plates and SLI enclosure, ensuring nearly all the heat flows via conduction through the isolators

Test Case	Description	Atmosphere	Pressure (Torr)	Average Adapter Plate Temperature (°C)	G10 Heater Plate Temperature (°C)	G10 Heater Plate Power (W)	Ti Heater Plate Temperature (°C)	Ti Heater Plate Power (W)	Duration
1.1	Vacuum, -30°C Chiller	Vacuum	6 +/-1	-31.1	20.6	0.75	21.1	1.24	2 hrs 37 min
1.2	Vacuum, -50°C Chiller	Vacuum	6 +/-1	-52	20.6	1.04	20.3	1.68	2 hrs 31 min
1.3	Vacuum, -70°C Chiller	Vacuum	6 +/-1	-69.6	21.7	1.29	21.9	2.1	2 hrs 28 min
2.1	CO_2, -70°C Chiller	CO_2	10-20	-65.8	20.5	1.43	22	2.27	4 hrs 50 min
2.2	CO_2, -50°C Chiller	CO_2	10-20	-49.5	21.1	1.19	22.1	1.88	2 hrs 34 min
2.3	CO_2, -30°C Chiller	CO_2	10-20	-29.6	21.5	0.88	22.5	1.4	2 hrs 38 min
3.1	GN_2, -30°C Chiller	GN_2	6 +/-1	-30.6	18.9	1.06	19.7	1.56	1 hr 56 min
3.2	GN_2, -50°C Chiller	GN_2	6 +/-1	-51.2	19.6	1.51	19.7	2.16	1 hr 47 min
3.3	GN_2, -70°C Chiller	GN_2	6 +/-1	-68.6	20.9	1.89	19.6	2.63	1 hr 48 min

Thermal Isolator Test Parasitic Heat Flows

- A heat flow balance about each heater plate was done to determine what percentage of the heater input actually flowed via conduction through the isolators compared to the parasitic heat load contributions due to the environment
- Two sources of parasitic heat flows were evaluated: gas conduction and radiation
- The percent parasitic heat loads were higher for the G10 isolators due to their higher thermal resistance
    - Max percentage was 10%, occurring in the -70°C GN_2 case
- Max percent parasitic heat load for the titanium isolators was 6%, also occurring in the -70°C GN_2 case

Value	Vacuum -30°C	Vacuum -50°C	Vacuum -70°C	CO_2 -30°C	CO_2 -50°C	CO_2 -70°C	GN_2 -30°C	GN_2 -50°C	GN_2 -70°C
G10 Heater Power (W)	0.74	1.01	1.27	0.86	1.17	1.41	1.05	1.48	1.86
G10 Total Parasitic Heat (W)	0.0087	0.0117	0.0149	0.068	0.0887	0.1035	0.1009	0.1455	0.1843
G10 Parasitic Heat as % of Heater Power (%)	1.2%	1.2%	1.2%	7.9%	7.6%	7.3%	9.6%	9.8%	9.9%
G10 Isolator Conduction (W)	0.73	1.00	1.25	0.79	1.09	1.30	0.95	1.34	1.67
Ti Heater Power (W)	1.22	1.65	2.06	1.38	1.85	2.22	1.54	2.12	2.58
Ti Total Parasitic Heat (W)	0.0094	0.0114	0.0151	0.066	0.0853	0.1001	0.0959	0.1316	0.1595
Ti Parasitic Heat as % of Heater Power (%)	0.8%	0.7%	0.7%	4.8%	4.6%	4.5%	6.2%	6.2%	6.2%
Ti Isolator Conduction (W)	1.21	1.64	2.05	1.31	1.76	2.12	1.44	1.99	2.42

Thermal Isolator Test Results

- After accounting for the parasitic heat flows and completing an uncertainty analysis, the final isolator conductances were evaluated
- G10 vacuum conductance:
  - EDU correlation: **0.004 W/K**
  - Calculated from isolator test (when extrapolated to temperature): **0.005 W/K**
  - Calculated value is 30% higher than the correlated value – this was not unexpected, especially given how sensitive the vacuum conductance is to contact regions and the lack of repeatability of the implementation of the G10 isolators
- G10 GN_2 conductance:
  - EDU correlation: **0.0089 W/K**
  - Calculated from isolator test (when extrapolated to temperature): **0.009 W/K**
  - The two values differ by only 1%, which is a nice validation of why the vacuum conductances differ by so much more – the addition of gas conduction makes all the uncertainties in contact areas null as the gas simply thermally shorts out those sections
- The titanium isolator conductance was expected to be between 0.011 W/K and 0.014 W/K, and all the final conductances were indeed within this range. The conductance in CO_2, which was most important, averaged out to about 0.0123 W/K.

Value	Vacuum -30°C	Vacuum -50°C	Vacuum -70°C	CO_2 -30°C	CO_2 -50°C	CO_2 -70°C	GN_2 -30°C	GN_2 -50°C	GN_2 -70°C
G10 Isolator Conductance									
Nominal Value (W/K)	0.0068	0.0066	0.0064	0.0076	0.0075	0.0073	0.0094	0.0093	0.0092
Uncertainty (W/K)	± 0.0003	± 0.0003	± 0.0003	± 0.0004	± 0.0003	± 0.0003	± 0.0004	± 0.0004	± 0.0003
Ti Isolator Conductance									
Nominal Value (W/K)	0.0116	0.0113	0.0112	0.0125	0.0123	0.0121	0.0143	0.0140	0.0137
Uncertainty (W/K)	± 0.0004	± 0.0004	± 0.0004	± 0.0005	± 0.0004	± 0.0004	± 0.0005	± 0.0005	± 0.0004

Flight Predictions

- Assuming Holden Crater winter and summer for worst-case cold (WCC) and worst-case hot (WCH) conditions for a baselined comparison, though the final landing site is Jezero Crater

- Pre-Correlation:

	WCC, 15 m/sec Wind		WCH, No Wind	
Camera/Location	Warmup Time, minutes	Warmup Energy, W-hr	Max. Camera Housing Temperature, °C	Max. Lens Temperature, °C
Front HazCams	33.7	11.2	35.5	34.6
Rear HazCams	31.8	10.6	34.5	33.7
NavCams	25.9	8.6	25.6	23.8
CacheCam	27.9	9.3	17.1	19.2

- Post-Correlation:

	WCC, 15 m/sec Wind		WCH, No Wind	
Camera/Location	Warmup Time, minutes	Warmup Energy, W-hr	Max. Camera Housing Temperature, °C	Max. Lens Temperature, °C
Front HazCams	28	9.2	38.7	38
Rear HazCams	27	9	37	36
NavCams	21	6.9	24	23
CacheCam	21	6.9	22	23

- After the correlation changes, the HazCams still have the longest warmup times, highest warmup energies, and hottest temperatures
    - 28-minute warmup time (9.2 W-hr warmup energy)
    - Max camera housing & lens temperature of 38-39°C
- As a result of the testing and correlation, the warmup times and energies decreased by ~20% and the maximum temperatures rose by ~3-4°C

Lessons Learned

- As with any thermal test, taking images and documenting the assembly of the test article and setup was critical. During model correlation, there was some difficulty in getting some components to correlate within a reasonable margin, which was attributed to design features not shown in the CAD model
- During the EDU GN_2 steady state warmup, the atmosphere thermocouple, located directly above the camera, noticeably rose in temperature as the camera approached steady state. It was being heated by the gas in the camera's vicinity – in the future, it could be beneficial to put multiple atmosphere thermocouples to characterize gradients in the gas. In this case, the atmosphere thermocouple only rose 3°C, so the effect was benign.
- For consistency, all bolted joints should have been torqued to their proper values – this was done for all the camera fasteners but not for any of the GSE fasteners nor the G10 thermal isolators
- When using a pressure gauge, be aware of whether it's reading absolute pressure or gas-dependent pressure
- By far the most significant lesson learned: be more cautious when developing a thermal isolator design meant to replicate the isolation of another design. Doing so adds another level of uncertainty in the correlation, particularly if that isolator design has not been characterized before. While the flight-like isolators were not available for the EDU thermal test, there were some improvements that could have been made to the G10 isolator design to make its conductance more deterministic.

Conclusions

- Both thermal tests were successful and all test objectives were met
- The EECAM thermal design was successful validated and proven to be robust – in general, the various EECAM components are much more thermally-coupled to one another than previously assumed, which allowed for a reduction in the conservatism of the thermal model
- The design of the GSE G10 isolators was not as effective as it could have been – however, the differences between the correlated and calculated values have been justified and the EECAM EDU correlations have been shown to be sound. There are no concerns with the final correlated parameters.
- The design of the flight titanium isolators has been shown to be extremely robust – their performance is independent of atmosphere and temperature, and easily verifiable with simple hand calculations.
- These tests provided enough risk reduction in the thermal design of the EECAMs that the flight units should be able to go through system testing without thermal issues.

Acknowledgements

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